

**Meteoroid Engineering Model (MEM)**

**Meteoroid Engineering Model (MEM)  
A Meteoroid Model for the Inner Solar System**

**H.McNamara, Space Environments Team – Marshall Space Flight Center**

**J. Jones, Department of Physics – University of Western Ontario**

**B. Kauffman – NASA Space Environments and Effects Program**

**R. Suggs, Space Environments Team – Marshall Space Flight Center**

**W. Cooke, Morgan Research – Marshall Space Flight Center**

**S. Smith, Morgan Research – Marshall Space Flight Center**

*National Aeronautics and Space Administration, Marshall Space Flight Center, AL USA 35812*

**Abstract.** In an attempt to overcome some of the deficiencies of existing meteoroid models, NASA's Space Environments and Effects (SEE) Program sponsored a three year research effort at the University of Western Ontario. The resulting understanding of the sporadic meteoroid environment – particularly the nature and distribution of the sporadic sources – were then incorporated into a new Meteoroid Engineering Model (MEM) by members of the Space Environments Team at NASA's Marshall Space Flight Center. This paper discusses some of the revolutionary aspects of MEM which include a) identification of the sporadic radiant with real sources of meteoroids, such as comets, b) a physics-based approach which yields accurate fluxes and directionality for interplanetary spacecraft anywhere from 0.2 astronomical units (AU) to 2 AU, and c) velocity distributions obtained from theory and validated against observation. Use of the model, which gives penetrating fluxes and average impact speeds on the surfaces of a cube-like structure, is also described along with its current limitations and plans for future improvements.

### 1.0 Background

Sporadic meteors are a diffuse background of meteoroid activity of cometary or asteroidal origins. They represent a continuous risk to spacecraft throughout the year, unlike meteor showers or storms. Showers and storms occur when the Earth travels close to a cometary orbit where the parent comet near perihelion sublimates and particles leave the surface of the comet. These particles are distributed out along the comets orbit creating a ring of dust and particles. The particle density is largest close to the comet when that comet is closest to the sun. If the Earth travels through this ring of meteoroids as the comets' orbit crosses the plane of the ecliptic a meteor shower or storm results. Although the risk to spacecraft is high during showers and storms, the sporadic meteoroid environment poses a greater risk as the integrated number is much greater than that of shower meteoroids. To mitigate the meteoroid risks for showers and storms spacecraft operators can often reorient their vehicle to point sensitive equipment away from the radiant, or they can slew solar panels edge on to minimize cross sectional area and close shutters to sensitive optics. The sporadic meteoroid background with its constant threat poses significant engineering challenges in mitigation. Often operators and designers choose to shield their spacecraft against the hypervelocity impacts. But the question arises...how much shielding is necessary and what parts of the spacecraft are most exposed?

To answer those questions spacecraft designers need to have access to an engineering tool that accurately models the locations of the sporadic meteoroid radiant, the sources of the sporadic meteoroids, their relative strengths and proper velocity distributions. But there are several different methods for modeling these desired parameters. Some models rely on in-situ dust measurements from space probes, zodiacal light observations, lunar micro-crater counts, impact counts from spacecraft, and ground based radar observations. However, extracting accurate mass and velocity information from impact craters is very difficult as they are not independent and on board spacecraft sensors can only detect particles smaller than one microgram. Other methods involve modeling the physics and distributions of the sporadic sources themselves, and not relying on incomplete data measurements. This paper briefly addresses the empirical models of the past, and their inadequacies and poses an alternative approach. We hope to address as well, the issues that

spacecraft designers and mission analysts are concerned with, specifically the flux of meteoroids of a certain mass or range of masses, the impacting speeds and distributions, and the direction from which those meteoroids are coming.

## 2.0 Other Models

The models of the past were mathematical models, simple or complex numerical expressions fit to observations from a variety of data sources patch-worked together. These expressions, though physically limited, defined the interplanetary meteoroid environment in terms of mass versus number density, velocity distribution, and meteoroid density. Most models also assumed that the sporadic background was omni-directional, an assumption that is known to be invalid. Grün's "Interplanetary Dust Model" a simple, easy-to-use equation, accurately fits the measured dust fluxes near Earth's orbit but does not contain directionality. It is this model that is described in NASA Technical Memorandum (TM) 4527. In addition to the flux equation, there is a velocity distribution developed by Cour-Palais based on photographic velocity determinations. The velocity distribution stated in the NASA TM has an average of 17 km/s at Earth. For Earth orbiting spacecraft that number is 19 km/s, which is quite low compared to new information from radar observations. This older velocity distribution did not work well with the Grün flux because Grün's equation was meant to be used with a meteoroid speed of 20 km/s, a flux weighted average. That value was justified based on two reasons, the first, cratering and destructive collisions depend on  $v^2$  and the average effect corresponds to a higher speed (over the average impact speeds on the moon from 13 to 18 km/s). Secondly, mutual collisions among meteoroids occur at higher speeds than impacts on the moon and on Earth because their eccentricity and inclination is generally larger than that of Earth, (Grün, 1985). Recently, Grün has updated this average sporadic speed at Earth to be around 35 km/s based on new data.

Divine's "Five Populations of Interplanetary Meteoroids" model uses complicated mathematics to obtain empirical fits for the orbital distributions of particles from a variety of data sources. Because the data came from multiple sources and due to the incompleteness of the measurements, simplifying assumptions were made to arrive at a solution. The current version of METEM, the model based on Divine's work, does not accurately model the sporadic directionality or velocity distributions. Divine's speed distributions were based on the Harvard Radio Meteor Project (HRMP), which provided the meteor orbital data. It was discovered by Taylor (Taylor, 1995) that a mistake had been made in the de-biasing of those speed distributions. The HRMP data is now known to contain biases towards the lower speeds. The biases are due to an absent correction for the initial radius effect which causes higher velocity meteors to be missed due to increased attenuation at increasing altitudes. This makes Divine's "core" distribution unreliable. Additionally, the Harvard dataset only applied to orbits that intersected the Earth's, leaving Divine to rely on interpolation methods for the un-sampled inner solar system. Recently, Divine's model has been updated to correct for the velocity bias. However, the fact remains that both of these models are still empirical models fit to observations at the Earth, mathematical models with gaps in measurements and no directionality. Another technique must be employed to model the larger particles damaging to spacecraft.

### 3.0 Our Model

The inaccuracies in the current meteoroid models led to a recent effort by the SEE program to develop a new meteoroid engineering model that incorporated a physics-based approach to modeling the sporadic meteoroid sources, radiants and their directionality, with validation against radar observations. The task was to construct a model that could predict the concentration and velocity distribution of meteoroids within the inner solar system from 0.2 AU to 2 AU, using observational measurements to constrain the physical model, rather than build one based on incomplete observations. Because micrometeoroid detectors on board space probes and satellites have observed highly directional fluxes of interplanetary dust particles that vary in particle size (Grün, 1985) and NASA is planning large oriented spacecraft such as Jupiter Icy Moons Orbiter (JIMO); incorporating directionality was of great importance in this model. Mitigating the risks to spacecraft depends on knowing which direction the flux is coming.

Previous work done by (Jones and Brown, 1993) show that the sporadic meteoroid environment as observed from Earth can be described by 4 major sources in 6 radiants distributed symmetrically about the celestial sphere in sun-centered coordinates. The primary sources of the Helion/Anti-Helion, North and South Apex, North and South Toroidal concentrations are short period comets, long period comets, and Halley family comets respectively. There is also a little understood component worth mentioning and that is modeled in this program, an asteroidal component. The specific details on the physics behind the model such as:

- How are the cometary orbits distributed?
- Which orbital elements are important?
- Comet sizes and sublimation rates
- Which perturbation forces are important, Poynting – Robertson, radiation pressures, etc.
- Modeling of the short period/long period comet orbit evolution
- De-biasing of observations (radar meteoroid velocities)
- Validation against observations

can be found in (Jones, 2003) and (Jones, 2001). A review of the engineering approach used in MEM is described below, along with results of the model.

The core of this program calculates an integral flux of number of particles/meter<sup>2</sup>/hour and average impacting speed in kilometers/second relative to the spacecraft. The idea is to construct the meteoroid environment at the spacecraft location and use a ray tracing algorithm to integrate over each surface of the vehicle the encountered flux and velocity from all of the sporadic meteoroid radiants. This is accomplished by transforming the velocity vector of the meteoroids orbit relative to the spacecraft into latitudinal and longitudinal coordinates, defined at a spacecraft radial location. Meteoroid velocity vectors and spatial densities are derived from a distribution of cometary meteoroid orbits taking into account the appropriate perturbation forces and assumptions discussed above. There are four sets of distributions one for each family of comets and the asteroidal component. With the relative velocity magnitude and a spatial density at the given heliocentric radius, a

meteoroid flux quantity is calculated. This flux quantity can be arranged by direction in a grid form from the relative velocity vector where each cell has the appropriate flux strengths and velocity weights applied to it. Inherent in the calculations are the de-biasing, mass-weighting, initial trail radius correction and relative strength corrections applied by Campbell-Brown in (Jones, 2003). For our simple cube spacecraft, each surface is evaluated for exposure to the meteoroid environment, integrating over each surface and over each grid point in the flux grid. The flux of meteoroids and average impacting speeds are computed for each exposed surface. The model is capable of computing the flux of mass ranges damaging to spacecraft,  $10^{-6}$  grams to 10 grams. For hypervelocity impact shielding, two penetration equations are implemented to calculate the integral flux that would just penetrate an equivalent aluminum thickness, given by the user. The penetration equations used are Fish-Summers and Cour-Palais with average meteoroid density of  $1.0 \text{ gram/centimeter}^3$ . Penetrations are computed using the normal components of the incoming velocities from each "visible" flux grid cell. These equations were chosen as they give adequate predictions of independent aluminum impact test data, with Fish-Summers being more conservative. More information about these penetration equations can be found in (Elfer, 1996). Final results are presented as flux of particles greater than and including a specific mass with average impacting speeds on each surface of a cube spacecraft along with the normalized velocity distribution for the entire spacecraft.

#### 4.0 Results from MEM

Below is a test case from MEM version 1.0. This scenario models a spacecraft flying at Earth's orbit 1 AU without the Earth. Data is based on flux of meteoroid particles greater than and including  $10^{-6}$  grams. Figure 1 shows a graphical representation of flux on each surface of a simple cube. Figure 2 represents the distribution of particles at the spacecraft location, 1 AU and Table 1 describes the average impacting speed on each surface.

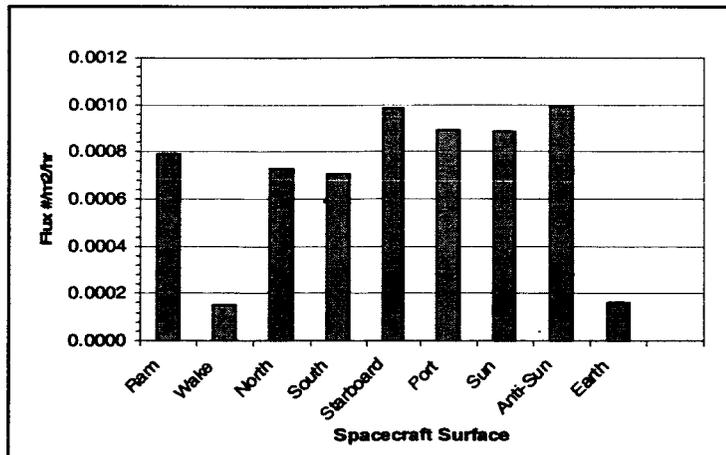


Figure 1. Flux on Spacecraft Surfaces 1 AU,  $10^{-6}$  g mass

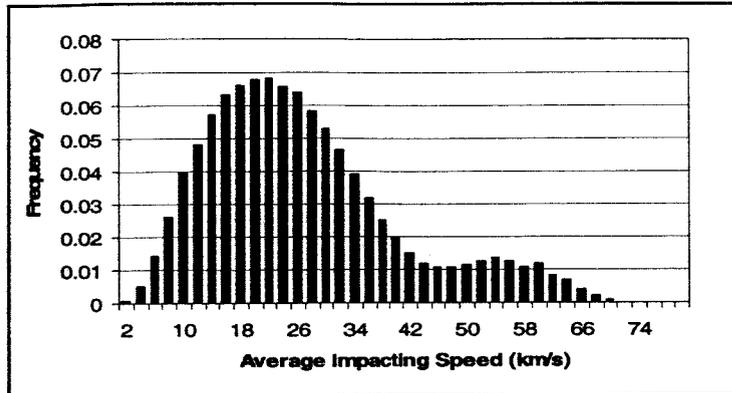


Figure 2. Total Speed Distribution

Ram	Wake	North	South	Starboard	Port	Sun	Anti-Sun	Earth
26	21.6	24	24.1	24.2	24	24	24.2	21.4

Table 1. Average Impacting Speed (km/s) by Surface

Note that MEM predicts an average flux weighted speed of meteoroids of 32.5 kilometers per second at Earth, compared to the older Grün value of 20 kilometers per second. This value agrees with the observations from the Canadian Meteor Observation Radar (CMOR) system.

### 5.0 User Interface

The MEM program was designed to have a simple and easy to understand user interface. For this current release, to use the tool, a user is required to input several parameters. First, a trajectory file(s) of the spacecraft that contains Julian day, components of the position in kilometers (X Y Z) and components of the velocity in kilometers per second. Next, the user can choose between two calculation types, log mass, or penetration equation. Log mass means the program will calculate fluxes of a certain log of the mass size. The penetrating flux calculation type requires an equivalent aluminum thickness of shielding and specifying one of the two choices of equations, Fish-Summers or Cour-Palais. With all inputs entered, the program will calculate the mass flux or penetrating flux, average impacting speeds and a speed distribution file. This first release only models a simple cube to give an idea of the difference in flux and speed each surface will encounter. This cube is assumed to have a fixed attitude, no spinning surfaces, where ram is oriented along the velocity vector, north and south surfaces point in the directions of ecliptic north and south, the port surface faces the inside of the orbit (towards the sun) and the starboard faces the outside of the orbit (towards deep space).

### 6.0 Current Limitations

The current release of MEM, delivered to the SEE program in May 2004, does not contain gravitational focusing. It is applicable initially as an interplanetary model only. The spacecraft orientation is assumed to be a simple cube with a fixed attitude oriented along the velocity vector. Velocity distributions on each surface are not calculated but an average impact speed is calculated. The relative strengths of the sources, the asteroidal contribution and velocity distributions are all areas that need further investigation. The uncertainties associated with size, shape, density, and velocities are issues that will be worked on over time and filling the gaps in the data are currently being worked by several groups including the environments team at NASA Marshall Space Flight Center.

### **7.0 Future Releases**

Future releases will incorporate gravitational focusing so that the program is applicable near planets and will be useful for lunar or Martian mission designs. Other updates will include additional surfaces pointed towards the sun/anti-sun and earth directions, spinning surfaces, different spacecraft orientations, velocity distributions on each surface, additional penetration equations and or user defined ones. Updates to the physics model will be included as more data is gathered, such as extending the model beyond Mars, incorporating annual variation in the sporadic background, and including distributions for meteor densities.

### **8.0 Summary**

This recent research effort has produced a new tool that will help spacecraft designers mitigate the risks posed by sporadic meteoroids. The directionality effects, source strengths and velocities presented in this model are an improvement over past models and with future releases and updates in the penetration equations and spacecraft orientations, it is our hope that this will provide a more reliable model for what interplanetary spacecraft will encounter outside of Earth's Orbit.

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